THE BENEFITS OF SLOW SPEED PUMPING

Paul M. Bommer, The University of Texas at Austin
David Shrauner, Zachry Exploration, Ltd.

MOTIVATION

One of the most significant operating costs (frequently the largest) associated with sucker rod pumping is the expense of pulling and repairing the rods, pump, and tubing. Many wells are pulled for repairs so often that they are marginally economic. This problem is made worse by the days of lost production associated with the down time.

This work demonstrates how pumping slowly can solve these difficulties, making marginal wells economic over a long period of time.

CUSTOMARY PRACTICE

As reservoirs deplete, there will come a time when a sucker rod pump installation can lift more liquid than the reservoir can deliver. Excess pumping capacity results in excessive wear from shock loads caused by fluid pound and unnecessary friction and stress fluctuations.

The customary method of limiting this damage is to pump intermittently. This is done by placing the unit on a time clock or by installing a pump-off controller.

Both methods have at least four drawbacks:

1. Intermittent pumping changes the frequency, but not the pumping speed. When the unit comes back on, the loads associated with motion and fluid pound reoccur.

2. During the time when the pumping unit is off, the reservoir is flowing liquid into the well bore. This flow builds a liquid level in the casing which creates back pressure on the producing formation. Maximum flow occurs with minimum back pressure which is achieved by keeping the column of liquid in the casing as small as possible.

3. Starting the unit from a dead stop requires the maximum power usage. The start phase is also a significant shock on the pumping unit, rods, and pump.

4. If the well produces any solids, the down time allows the solids to settle. This will increase the frequency of stuck plungers.

Therefore, the customary methods cannot eliminate all the shocks, unnecessary pump cycles, and unnecessary power use, nor can they provide the minimum back pressure against the reservoir at all times.

THE SLOW SPEED SOLUTION

The faster a unit pumps, the larger the number of cycles there are and the sooner the rods reach a fatigue limit. The number of pumping cycles and the stresses caused by motion can be minimized if the unit is pumped as slowly as possible using the longest stroke possible to produce the flow rate the reservoir can deliver. When done this way, long run times are normal.

TOWARDS INFINITE LIFE

A sucker rod subjected to a fluctuating load can tolerate only a given number of cycles before the rod fails. Goodman's work[1] considered steel specimens that were cycled to a maximum stress and then back to the initial minimum stress. He considered 4 million cycles before failure as an "infinite life". Other modifications define between 1 million and 10 million cycles as "infinite life"[2].

The Modified Goodman Diagram (MGD) we currently use for API sucker rod analysis[3] is shown in Fig. 1. This diagram shows stress as a fraction of the minimum tensile strength of a rod. The API maximum line is below the maximum suggested by Goodman, causing the range of allowable stresses to be smaller than those allowed by Goodman. The intercept of the maximum stress line at zero minimum stress is defined as the fatigue strength of the rod and is related to the required number of cycles [2]. Goodman's experimental correlation has a fatigue strength of one half the minimum tensile strength and was for 4 million cycles. The API modification of Goodman's diagram has a fatigue strength of one quarter of the minimum tensile strength and the calculated number of cycles is on the order of 10 million. A rod will tolerate more cycles if the required fatigue strength is a smaller fraction of the tensile strength of the rod. In fact, the expected life (N_f) is an exponential function of fatigue strength (S_f) as shown by equation (1) where a and b are properties of the rod [2]. The rod properties used for the purposes of this paper are shown in Table 1.

$$S_f = aN_f^b \qquad \text{….. (1)}$$

It is very important to note that Fig. 1 is only for fluctuations in tension. A rod with the maximum load in tension and the minimum load in compression will have a shorter life than the same maximum load with the minimum load kept in tension. This is because the stress fluctuation created with the maximum load in tension and the minimum load in compression will fall on a larger fatigue strength, thus a shorter life, line.

The equation that describes the API maximum stress line is shown by equation (2),

$$\frac{\sigma_{\max}}{T_{\min}} = \frac{S_f}{T_{\min}} + 0.5625\frac{\sigma_{\min}}{T_{\min}} \qquad \text{….. (2)}$$

where $\frac{S_f}{T_{\min}} = 0.25$.

It is customary to reduce the maximum allowed stress by a service factor that depends on the corrosiveness of the produced fluid and whether it is successfully inhibited. For a given minimum stress, any maximum stress that plots on or below the API maximum line is considered a safe fluctuation, when adjusted by the appropriate service factor. The farther below the API maximum allowed stress line a maximum stress falls, the longer the service life. Slower pumping produces a relatively smaller maximum stress, but also a larger minimum stress as both friction and acceleration loads are reduced, resulting in a smaller stress fluctuation. The comparative number of allowed cycles increases because the stress fluctuation now falls below the original and has a smaller fatigue strength, as shown by equation (1).

A sucker rod string will be subjected to a maximum load during the up stroke and a minimum load during the down stroke. This is shown on the ideal surface dynamometer card of Fig. 2. The parallelogram shape of the ideal card is because of rod stretch.

Ideally, the rods experience one stress fluctuation per cycle. A stress fluctuation is when a load changes not only magnitude but direction. For the ideal shape of Fig. 2, one stress fluctuation is created by raising the rods to a maximum load during the up stroke and lowering them to a minimum load during the down stroke. There often are many smaller load direction changes during a stroke that increase the number of stress fluctuations per cycle. Figure 3 superimposes the actual surface dynamometer card on the ideal card. Figure 3 shows several minor load fluctuations in addition to the major fluctuation caused by the maximum and the minimum loads. The minor fluctuations in Figure 3 are more easily characterized if the dynamometer card is shown as a strip beginning at the start of the up stroke and finishing at the end of the down stroke as shown in Figure 4.

The effect of minor fluctuations on rod life can be estimated using the Palmgren-Miner Rule [2], shown in equation (3).

$$D(SF) = N_T \sum_{i=1}^{j} \frac{n_i}{N_{fi}} \qquad \text{….. (3)}$$

Figure 4 shows that all the fluctuations occur during one cycle, so in equation (3) $n_i = 1$. The number of cycles associated with each fluctuation (N_f) is a function of the fatigue strength line upon which the fluctuation falls. D is the accumulated damage to failure. In a perfect environment D=1. The service factor (SF) allows for a corrosive environment and is generally taken as a fraction less than 1. For any fluctuation, the fatigue strength can be predicted using equation (2) and the accompanying fatigue life predicted using equation (1). Finally, the total expected life of the rod (N_T) can be estimated using equation (3).

SLOW SPEED PUMPING

If the pump can lift more liquid than the reservoir can deliver, it is possible to reduce the speed of a unit to where the lift capacity closely matches the production rate of the reservoir. The necessary speed reduction can be achieved by replacing the unit or prime mover sheave or both. Even slower pumping can be achieved by the use of a second speed reducer known as a jack shaft which fits between the prime mover and the gear box of the unit.

JACK SHAFT DESIGN

A jack shaft is a shaft mounted on two bearings that have an input and an output sheave. The input sheave is attached to the prime mover sheave with a power belt; the output sheave is similarly attached to the pumping unit gear box sheave. Figure 5 shows a jack shaft schematic and a prefabricated unit with the belt guard removed for viewing. The speed of the pumping unit with a jack shaft can be calculated using equation (4).

$$N = \frac{N_{pm}}{Z} \frac{d_{jso}}{d_u} \frac{d_{pm}}{d_{jsi}} \quad \text{(spm)} \qquad \text{….. (4)}$$

As a general rule, the cost of the installed jack shaft is less than the cost of one tubing pulling job. In our experience, at slow speeds the gear box requires no modification to insure proper gear lubrication.

SLOW SPEED PUMPING RESULTS

Two case histories are presented to demonstrate the utility of this approach. When correctly designed, slow speed pumping always produces results similar to the examples cited.

Example No. 1, Winkler County, Texas: This well was pumping from a depth of 3,210’ at a speed of 13.5 spm. The rods had parted five times in 24 months. The surface dynamometer card is shown in Figure 3 and the load strip for one cycle is shown in Figure 4. The pump barrel is filling about 65% on each stroke and Figure 4 indicates four fluctuations per stroke. The loads and stresses for each fluctuation and the theoretical rod life based on equation (3) are shown in Table 2. For comparison purposes, the service factor used in equation (3) is 1.0.

The peak polished rod load and the minimum polished rod load are the first fluctuation.

This unit was slowed to 7.5 spm. The surface dynamometer card at the slower speed is shown in Figure 6 and the load strip chart is shown in Figure 7. The loads and stresses for each fluctuation and the theoretical rod life at 7.5 spm are shown in Table 3.

The result gained by slowing to 7.5 spm is a 20 fold increase in theoretical rod life. This unit ran for three years without a pulling job. This is a 7.5 fold increase in run time in practice. By slowing to 7.5 spm the unit lifts 36,615 tons/day less weight and requires 8 Hp less power.

Example No. 2, Gonzales County, Texas: This well was pumping from a depth of 8,400’ at a speed of 6.25 spm. The rods had parted six times in 34 months. The surface dynamometer card is shown in Figure 8 and the load strip for one cycle is shown in Figure 9. The pump barrel is filling about 40% on each stroke and Figure 9 indicates five fluctuations per stroke. The loads and stresses for each fluctuation and the theoretical rod life based on equation (3) are shown in Table 4.

This unit was slowed to 4 spm. The surface dynamometer card at the slower speed is shown in Figure 10 and the load strip chart is shown in Figure 11. The loads and stresses for each fluctuation and the theoretical rod life at 4 spm are shown in Table 5.

The result gained by slowing to 4 spm is a 4.3 fold increase in theoretical rod life. This unit ran for five years without a pulling job. This is a 10 fold increase in run time in practice. By slowing to 4 spm the unit lifts 20,140 tons/day less weight and requires 6 Hp less power.

The discussion to this point has focused on extending rod life by pumping more slowly. It is important to remember that tubing and pump wear go hand in hand with rod life. By pumping slowly, tubing and pump life will also be extended.

THE DETERMINATION OF MAXIMUM RATE

For sucker rod pumped wells that have an excess pump capacity it is normally obvious what the well will produce. If this is not so, the pumping unit can be run continuously until a daily rate is established. A representative dynamometer card will show how much the pump is filling on each stroke. Fluid levels can yield useful data, if used carefully, because a small slug of fluid or foam in the annulus will appear as a fluid level and indicate a greater inflow from the reservoir than is actually present. However the initial estimate is made, it is excellent practice to check the final design using a dynamometer after the well has pumped for several days.

CONCLUSIONS AND RECOMMENDATIONS

Matching the pumping capacity to the inflow of the reservoir is the key to maximum liquid production and long run life. For wells with excess pump capacity, the best way to achieve this is by slowing down the pumping rate. The smallest possible pumping speed to provide the required capacity will:

(1) produce 100% of the liquids available from the reservoir
(2) reduce rod stress fluctuations and shock loads
(3) cause the unit and rods to do the minimum amount of work
(4) use the minimum amount of power
(5) keep the pump in motion to prevent solids from sticking the plunger
(6) provide the longest run time possible
(7) create the largest profit by maximizing production and minimizing pulling frequency.

Our experience with more than 500 sucker rod-pumped wells in four states has verified these claims.

Every sucker rod pump that has excess capacity should be slowed so as to pump continuously and match the daily flow from the reservoir. The well conditions after a change should be checked using dynamometer analysis.

REFERENCES

(1) Goodman, John, “Mechanics Applied to Engineering”, Longmans, Green and Co., London, 1914, pp. 631-636.
(2) Shigley, J.E., Mischke, C.R., and Budynas, R.G., “Mechanical Engineering Design”, 7th ed., McGraw-Hill, New York, 2004, Chapter 7.
(3) API Recommended Practice 11BR, 8th ed., API, Dallas, October 1989.

NOMENCLATURE AND UNITS

$\sigma_{\max}$ Maximum allowed stress on a sucker rod (psi)

$\sigma_{\min}$ Minimum stress on a sucker rod (psi)

a and b are rod properties that relate the number of cycles to fatigue strength [2]
a has units of psi and b is dimensionless

D accumulated damage to failure, generally taken to be 1.

d_{jsi} pitch diameter of jack shaft input sheave (inches)

d_{jso}	pitch diameter of jack shaft output sheave (inches)
d_{pm}	pitch diameter of prime mover sheave (inches)
d_u	pitch diameter of pumping unit sheave (inches)
F_o	Weight of the fluid (lb_f)
N	pumping speed (strokes/minute or spm)
N_f	number of cycles associated with a given fatigue strength
N_{pm}	prime mover speed (rpm)
N_T	total number of cycles for a set series of load fluctuations
n_i	number of cycles at a given stress level (σ_i)
S	polished rod stroke length (inches)
S_f	fatigue strength (psi) associated with a set number of cycles
SF	service factor, generally decreases rod life or maximum stress
T_{min}	Minimum tensile strength of a sucker rod (psi)
W_{max}	Maximum or peak beam load (lb_f)
W_{min}	Minimum beam load (lb_f)
W_{rf}	Weight of the rods buoyed in the fluid (lb_f)
Z	pumping unit gear box ratio (revolutions/stroke)

Table 1
Rod Properties

API Grade	Minimum Tensile Strength - psi	Ultimate Tensile Strength - psi	Rod Constant a - psi	Rod Constant b
C	90,000	110,000	125,000	-0.105
K	85,000	100,000	113,000	-0.100
D	115,000	140,000	160,000	-0.110

Table 2
Example No. 1 Loads, Stresses, and Total Rod Life at 13.5 spm

Fluctuation Number	Max Load Lbs	Min Load Lbs	Max Stress psi	Min Stress psi	Sf psi
1	8185	2628	18560	5959	15208
2	7435	6797	16859	15413	8190
3	6797	6421	15413	14560	7223
4	5820	5557	13197	12601	6109
	Total N	512	million cycles using equation (3)		

Table 3

Example No. 1 Loads, Stresses, and Total Rod Life at 7.5 spm

Fluctuation	Max Load	Min Load	Max Stress	Min Stress	Sf
Number	Lbs	Lbs	psi	psi	psi
1	7160	3938	16236	8930	11213
2	7160	6730	16236	15261	7652
3	6981	6730	15830	15261	7246
4	4475	4000	10147	9070	5045
	Total N	10440	million cycles using equation (3)		

Table 4

Example No. 2 Loads, Stresses, and Total Rod Life at 6.25 spm

Fluctuation	Max Load	Min Load	Max Stress	Min Stress	Sf
Number	Lbs	Lbs	psi	psi	psi
1	20000	12740	33278	21198	21354
2	18540	17140	30849	28519	14807
3	17540	14140	29185	23527	15950
4	13740	13340	22862	22196	10376
5	13940	13740	23195	22862	10335
	Total N	81	million cycles using equation (3)		

Table 5

Example No. 2 Loads, Stresses, and Total Rod Life at 4 spm

Fluctuation	Max Load	Min Load	Max Stress	Min Stress	Sf
Number	Lbs	Lbs	psi	psi	psi
1	18850	14500	31364	24126	17793
2	17884	16724	29757	27827	14104
3	17207	16144	28631	26862	13521
4	17000	15757	28286	26218	13539
5	17110	16530	28469	27504	12998
	Total N	349	million cycles using equation (3)		

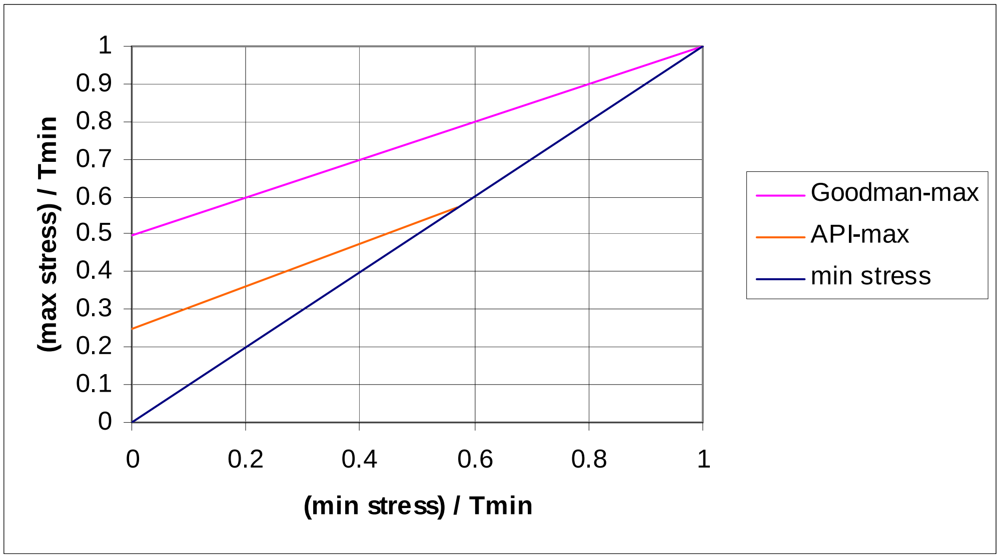

Figure 1 – Modified Goodman Diagram

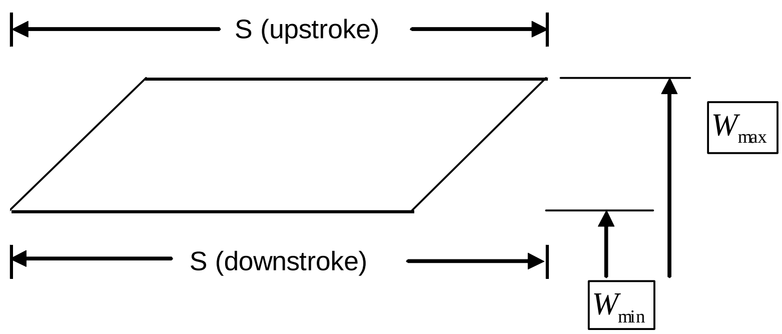

Figure 2 – Ideal Surface Dynamometer Card

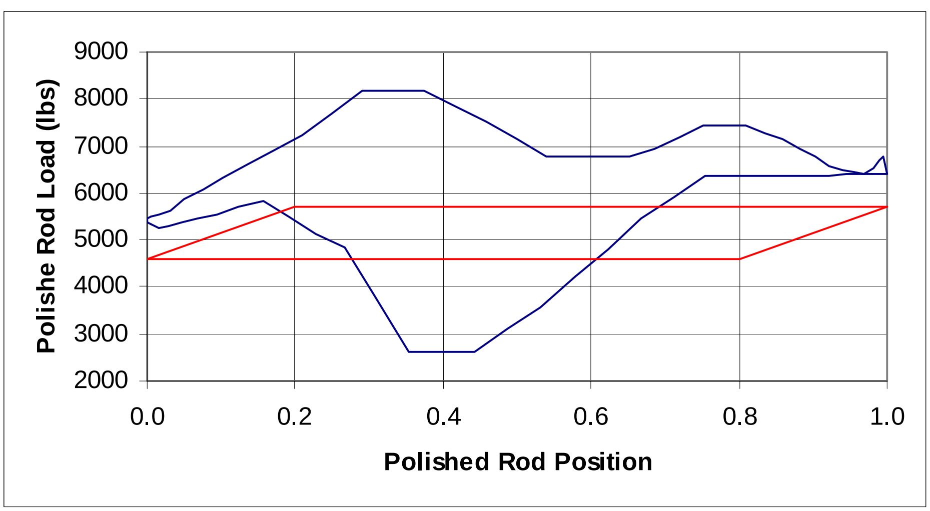

Figure 3 – Actual and Ideal Dynamometer Cards

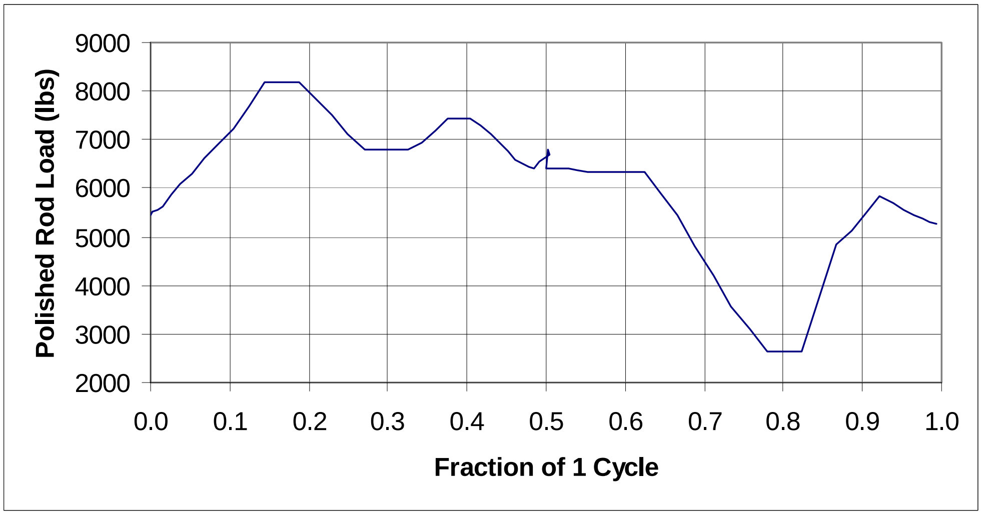

Figure 4 – One Stroke (from Fig. 3) Plotted as a Load Strip

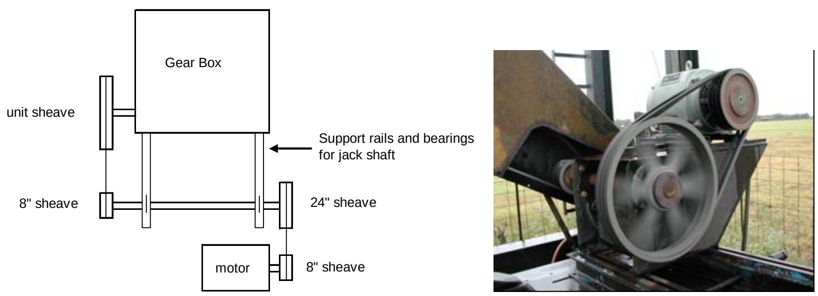

Figure 5 – Jack Shaft

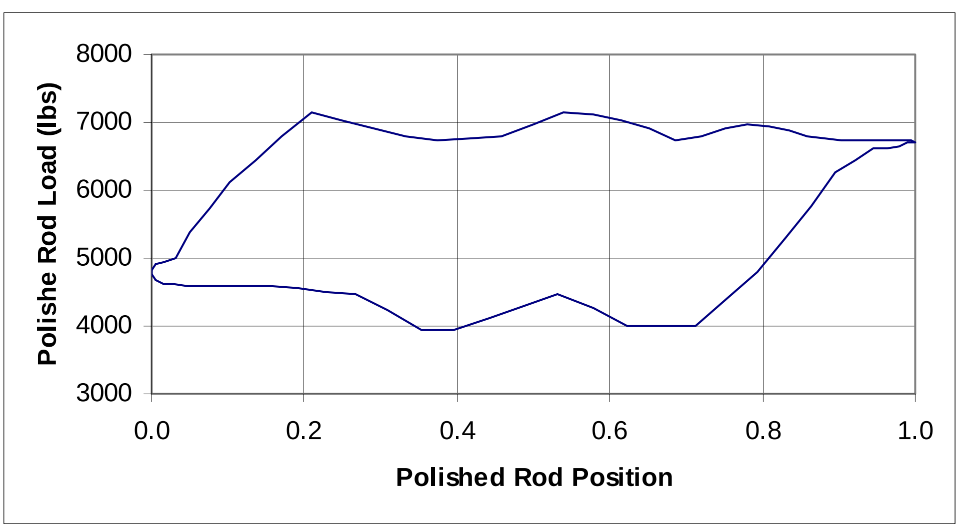

Figure 6 – Example 1 at 7.5 spm

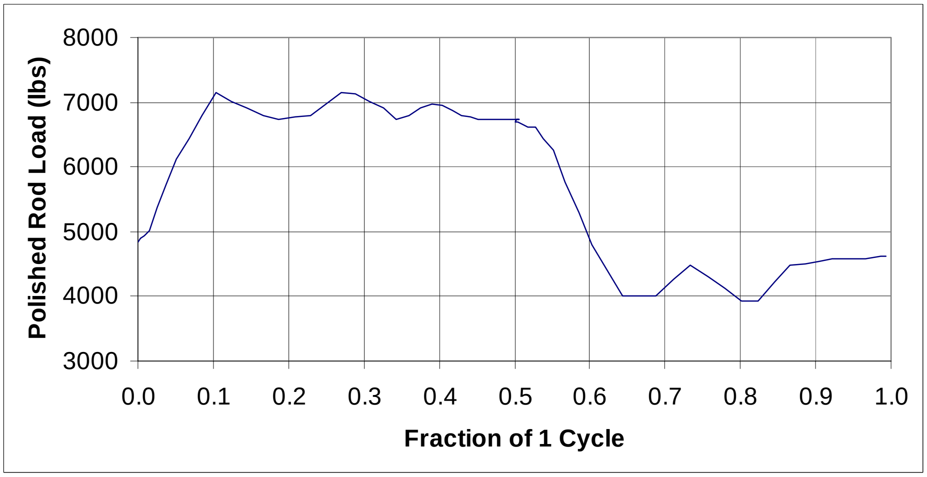

Figure 7 – Load Strip Chart for Example 1 at 7.5 spm

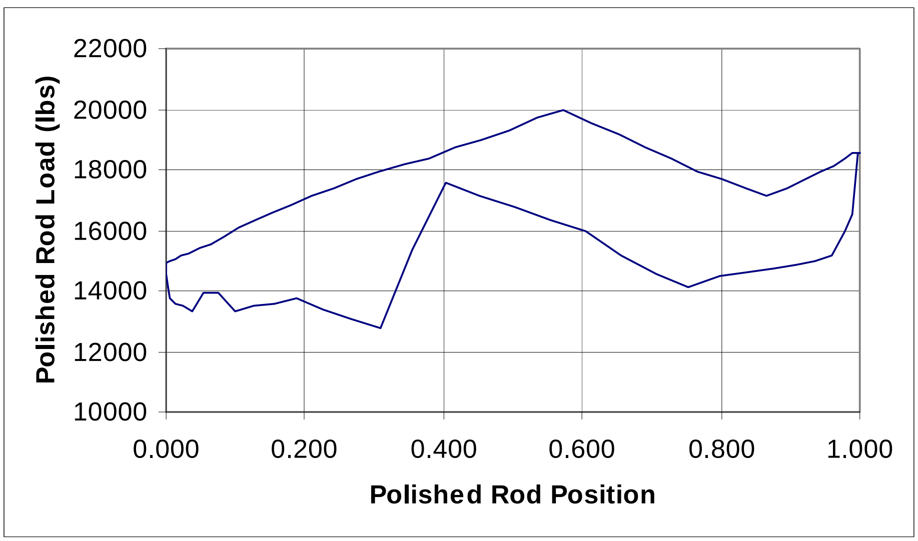

Figure 8 – Example 2 at 6.25 spm

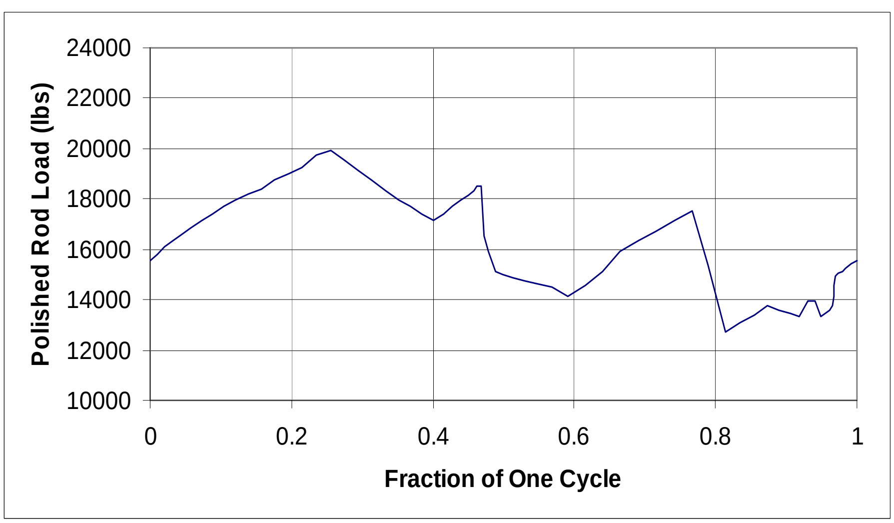

Figure 9 – Load Strip Chart for Example 2 at 6.25 spm

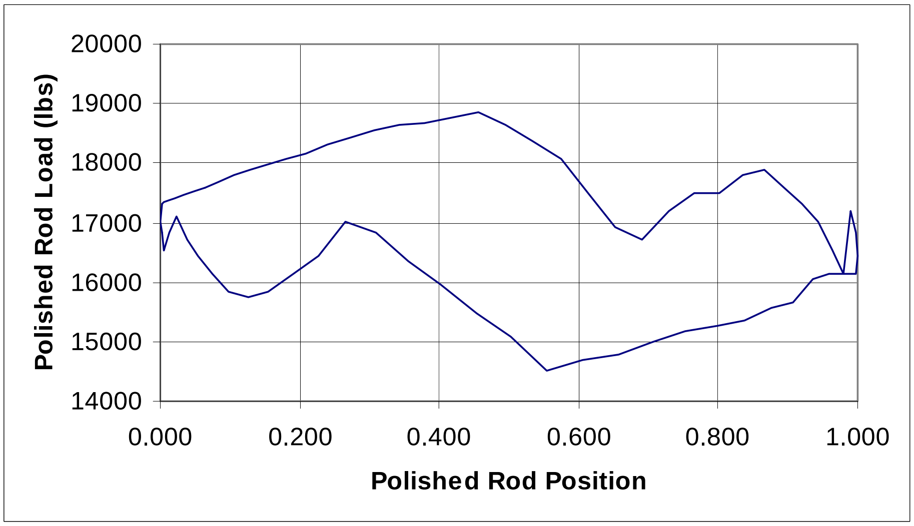

Figure 10 – Example 2 at 4 spm

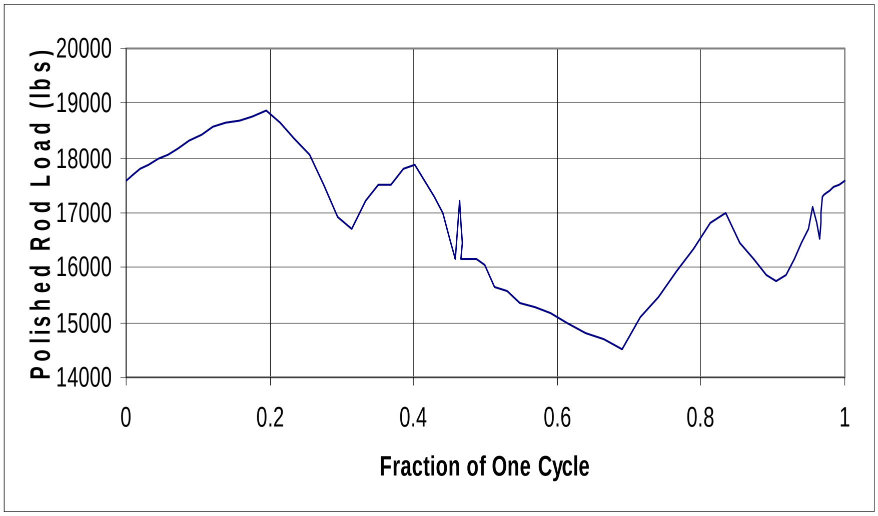

Figure 11 – Load Strip Chart for Example 2 at 4 spm